

# High Gain Antenna Gimbal for the 2003-2004 Mars Exploration Rover Program

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## Abstract

The High Gain Antenna Assemblies built for the 2003-2004 Mars Exploration Rover (MER) missions provide the primary communication link for the Rovers once they arrive on Mars. The High Gain Antenna Gimbal (HGAG) portion of the assembly is a two-axis gimbal that provides the structural support, pointing, and tracking for the High Gain Antenna (HGA). The MER mission requirements provided some unique design challenges for the HGAG. This paper describes all the major subsystems of the HGAG that were developed to meet these challenges, and the requirements that drove their design.

## Introduction

### MER Overview

The 2003-2004 Mars Exploration Rover mission consists of two long-range rovers that carry a payload of science instruments. The goal of the mission is to determine the history of climate and water at sites on Mars where conditions may once have been favorable to life. Two landing sites were chosen (Gusev Crater and Meridiani Planum) because they offer evidence that liquid water was once present. The science instruments will be used to read the geologic record at each site and to determine how suitable the conditions may have been for supporting life. The two rovers were named “Spirit” and “Opportunity” and were launched in June and July of 2003 with a scheduled Mars landing in January of 2004. Each rover has a mass of approximately 180 kg and has a range up to 100 meters per Martian day (~24 hours and 39 minutes) [1].

Figure 1 shows the rover in its deployed configuration. The topic of this paper, the High Gain Antenna Gimbal, can be seen on the top deck of the rover along with the Low Gain Antenna and the Panoramic Camera Mast Assembly. The HGAG provides the pointing and tracking capability for the High Gain Antenna RF communication system.

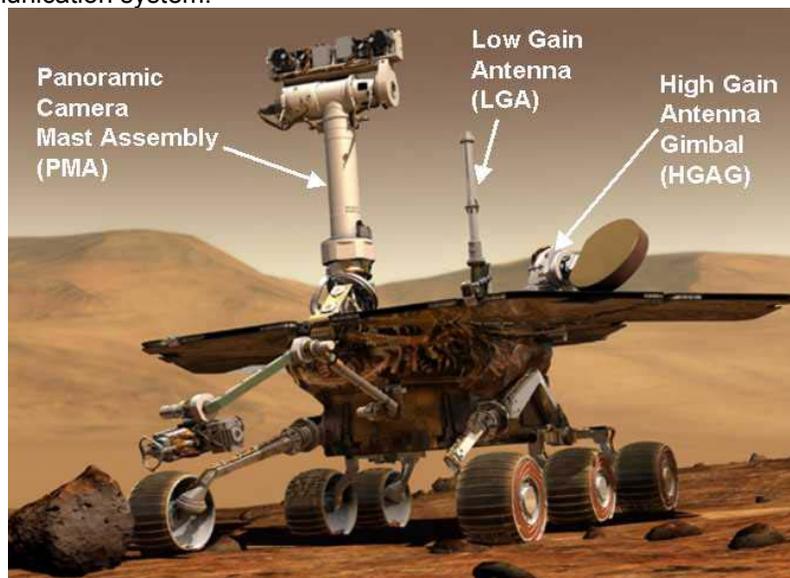


Figure 1. Mars Exploration Rover [1]

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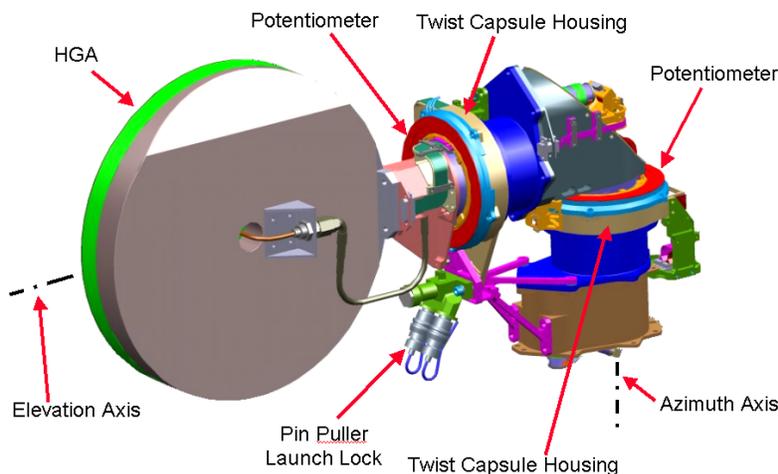
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### HGAG Program Discussion

The HGAG program was a cooperative effort between Jet Propulsion Laboratory (JPL) and Ball Aerospace & Technologies Corp. (BATC). The overall design architecture and initial drive train component sizing for the gimbal were established at JPL. The design was then turned over to BATC who was responsible for the final detail design, production, and test of the HGAG. A number of design components (motors, harmonic drives, potentiometers, RF rotary joints and flex cables) were specified early in the design process by JPL and they were delivered to BATC as customer supplied components for use in the HGAG design.

### HGAG Design Overview and Driving Requirements

The gimbal consists of two drive mechanisms mounted at 90 degrees to one another. The High Gain Antenna is mounted at the end of the elevation drive and both the elevation drive and antenna are mounted in a cantilevered fashion on the azimuth drive. This configuration accommodates the confined packaging requirements for launch on the rover while providing the necessary field of view and rotation angles for the HGA. The position of each drive is monitored using motor encoder information. In addition, potentiometers are incorporated into each drive to provide gross position determination in the case of a power cycle condition during the mission. Figure 2 shows the HGAG with the HGA attached.



**Figure 2. HGAG with HGA attached**

The assembly requires a locking mechanism to prevent drive rotation under launch and landing loads. This was accomplished by incorporating a single pyrotechnic pin puller, with redundant NASA Standard Initiator (NSI) charges, to lock both the azimuth and elevation drives. Once on Mars, the pin puller is fired and the drives are freed to rotate away from their stowed position. During deployment, the azimuth drive moves through a spring-loaded gate mechanism that closes once the drive has passed. After it is through the gate, the azimuth drive can no longer return to the original stowed position, protecting against potential interference between the HGA and other rover components during elevation drive rotation.

Because of the somewhat large angles of rotation ( $280^\circ$  azimuth and  $234^\circ$  elevation), and the need to pass power and signal electronics over both the azimuth and elevation drives, two twist capsules were developed to house the flex cables. In addition, the RF signal from the antenna also needs to pass through the elevation and azimuth drives while meeting a specified RF signal loss budget. Both the flex cable twist capsule and the rotating RF system will be described in this paper.

The Mars operating environment for the gimbal assembly provided specific challenges during design and test of the hardware. The dusty Martian environment requires special attention to mechanism contamination control, the thermal environment requires specific external surface treatments and heaters, and stringent planetary protection guidelines dictated high bake-out temperatures prior to launch that drove material and design choices. Drive testing was performed under expected operating temperatures, atmospheric pressures, and loads. Table 1 summarizes the significant driving requirements for the HGAG design.

**Table 1. MER HGAG significant driving requirements**

Requirement	Value	Unit
HGAG mass allocation (no HGA)	4.5	kg
Distance from HGA boresight to Azimuth Axis	0.33	m
Azimuth Drive Angular Rotation	280	deg
Elevation Drive Angular Rotation	234	deg
Minimum mechanical control and knowledge	0.5	deg
Drive operational step size	0.2	deg
Minimum drive rotation speed	0.78	RPM
Operating voltage range	22.5 to 34	V
Maximum MER incline with respect to gravity during operation	40	deg
Quasi-static design load (stowed)	45	g
Stowed first modal frequency (minimum)	50	Hz
Deployed first modal frequency (minimum)	14	Hz
Contamination control bake out temperature	110	C
Survival temperature range (non-bake out)	-120 to 60	C
Operating temperature range	-70 to 45	C
Motor revolution limit (testing / flight)	2.5E+06	revs
RF loss between HGA and Rover bulkhead	1.8	dB

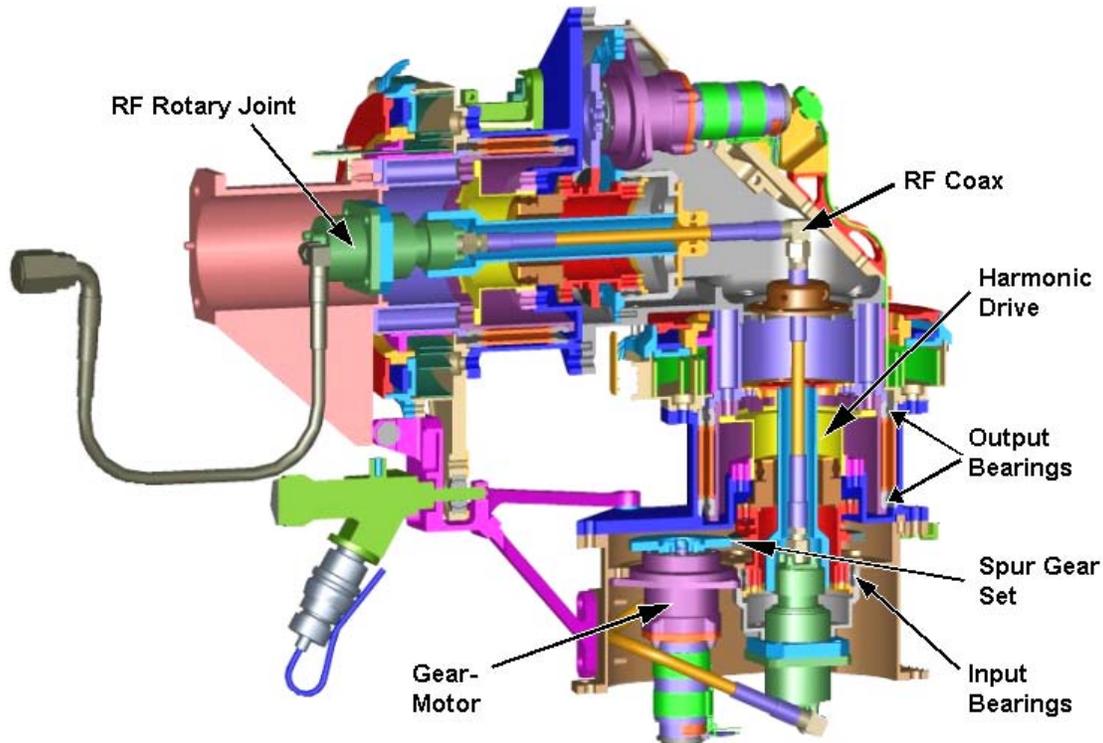
Three HGAA assemblies, 2 flight and one Engineering Model (EM), were delivered to JPL during the third quarter of 2002 for integration into the rover assemblies. The flight assemblies were successfully integrated and launched aboard the two Mars Rover missions, “Spirit” and “Opportunity”, during the summer of 2003 for arrival on Mars in January 2004. The engineering model was integrated on the EM Rover that is currently being used for mission control testing at Jet Propulsion Laboratory.

### **Design Discussion**

#### Drive Train

The gear train and RF system were designed concurrently to accommodate packaging and performance requirements. While the expected maximum external torsion load on the azimuth drive (2.9 Nm starting and 2.1 Nm running) is larger than the elevation drive (1.3 Nm starting and 0.6 Nm running), both drives were designed to accommodate the higher azimuth drive loads. In order to simplify the design, analysis, manufacturing, and assembly of the gimbal, both drives use identical gear trains that consist of a gear motor, spur gear stage, and a harmonic drive that combine to produce a 5424.7:1 gear reduction. A cross section view of the system is depicted in Figure 3. Early design trades included a more modular design, with the RF coax routed external to the main gimbal structure. This approach simplified the gear train design (and should therefore be considered for future gimbal designs) but required additional envelope external to the gimbal. Because of the tight packaging requirements on the MER, the decision was made to route the coax cables internally.

By assuming worst-case performance for all drive train components in the mechanism analysis, the need to pre-screen components prior to assembly was eliminated. Overall, simple and robust design principles were used to minimize the gimbal's sensitivity to variability in the performance of each component.



**Figure 3. HGAG cross-section**

#### Drive Bearings

The HGAG drives each contain two pairs of back-to-back mounted angular contact bearings. Both bearing pairs were manufactured by Timken Super Precision (MPB) and were lubricated at Ball Aerospace & Technologies Corp. The larger drive output bearings are required to carry the axial, radial, and moment loads generated during launch, landing, and MER maneuvering. The smaller drive input bearings are required to support the harmonic drive input loads as well as the radial and moment loads from the gear motor to harmonic drive spur gear stage. The bearings are made from 440C stainless steel (which helps to match the CTE of the surrounding titanium housings) and have phenolic retainers. Because of the operating environment on Mars as well as the mechanism life requirements, all the bearings are lubricated with Brayco Oil Company 815Z oil along with a 10% grease fill of Braycote 601. Although this lubrication allows the HGAG to survive the operating conditions and meet its life requirements, it does significantly increase the starting and running torque of the system at the cold operating temperatures. The increase in cold temperature starting and running torque made it critical that the minimum diameter bearings were chosen that could meet our structural load and packaging requirements. In both cases, the bearing pairs employ a "hard preload" assembly that utilizes precision shims to achieve the desired preload in the bearing set. After assembly, the bearing set preload and stiffness were verified by running torque and load tests.

#### Gear motor

In an effort to minimize the number of different drive components used on the overall MER system, the majority of mechanisms employ one of two brush DC motor sizes supplied by Maxon Corporation. The large gear reduction in the HGAG mechanism allows the gimbal to use the smaller Maxon REO20 motor (20-mm diameter), in lieu of the larger Maxon RE25 motor (25-mm diameter). By using the smaller motor, the HGAG design saves mass and reduces power consumption. Nearly all of the gear train calculations assumed the worst-case performance REO20 motor (except for mechanism

strength margin analysis where the maximum performance motor was used). The assumed motor had the lowest torque constant, the minimum speed constant, and the maximum armature resistance.

The gear motor assemblies were supplied by Starsys Corporation and used a three-stage, 81.37:1, planetary gearbox to minimize the effects of viscous losses caused by the bearings and harmonic drive on the motor. Once again, the gear motor analysis assumed worst case starting torque and no load running torque for the gear motor, as reported by Starsys.

#### Spur Gear Stage

Since the RF system is routed coaxial with the drive axis of rotation, a spur gear stage is used to offset the gear motor. The spur gear stage also provides a 1.33:1 gear reduction. Both the gear motor's pinion gear and the spur gear were made from 15-5 PH corrosion resistant steel. The spur stage was lubricated with MoS<sub>2</sub> filled Braycote 601 to meet the mechanism's life requirements.

#### Harmonic Drive Stage

The HGAG used a custom-built, hollow shaft harmonic drive made by HD Systems, Inc. The harmonic drive was based on HD Systems' standard model SHF 14-50 drive (with a 50:1 gear ratio) with changes made to accommodate the mounting requirements for the HGAG. This harmonic drive was chosen for the following reasons:

- Hollow design accommodated RF routing
- High gear reduction in a compact package
- Drive stiffness was high enough to meet accuracy requirements but low enough to prevent damaging hardware inside and outside the gear train when the mechanism rotates into its hard stops
- The drive was sufficiently accurate (low backlash, small hysteresis, and high repeatability)

For the harmonic drive, JPL initially explored using special aerospace grade materials recommended by HD Systems, Inc. that would be less susceptible to cold embrittlement. However, based on the limited flight history for the special grade materials and the limited development time for the MER program, JPL chose to use the standard commercial materials instead. Because of this decision, additional cold temperature / high load testing was required on the EM unit to validate the robustness of the harmonic drive.

#### Gear train Analyses

The principle analyses performed on the gear train were:

- Ensuring the motor would not overheat during worst-case loading and duty cycles. (As the motor runs, current flowing through the motor's armature warms the windings. Exceeding the maximum allowable winding temperature of 110°C would damage the motor).
- Ensuring the gimbal would meet its pointing accuracy requirements (backlash, hysteresis, wind-up)
- Assessing whether the mechanism would backdrive under MER mobility loads (induced by situations like driving over or off of large rocks).
- Ensuring that the mechanism would not damage itself or surrounding hardware if the mechanism drove into a hard stop at peak voltage.

#### Motor Overheat Analysis

Each drive was required to perform the following operations in rapid succession at both protoflight operating temperature extremes while at the minimum operating voltage:

1. Slew from hard stop to hard stop at 6 deg/sec
2. Stall for 2 seconds against the hard stop at the motor current limit
3. Slew back to the other stop at 6 deg/sec
4. Slew back 180 deg at 6 deg/sec
5. Rotate one 0.2 deg step (i.e. overcome starting torque)

This test was designed to ensure that the drive would be able to perform operational requirements, even after the Rover suffered a power reset condition. Thus, if the drive was at the end-of-travel hard stop, ground controllers could home the drive (1<sup>st</sup> slew plus 2 second stall), and then send the gimbal to the end-of-travel hard stop as if to resume communications (2<sup>nd</sup>

slew). If the earth's trajectory then forced the drive to "flop," the drive would slew 180 degrees in the opposite direction (3<sup>rd</sup> slew). Finally, overcoming the starting torque again and moving in 0.2 deg increments is required to resume the regular operation duty cycle.

Since the viscosity of the Braycote grease increases non-linearly with a reduction in temperature, meeting this requirement was a challenge. Development testing suggested that the no load running torque for the input bearings, harmonic drive, and output bearings increased significantly when the temperature drops from +25°C to -70°C (at 50 RPM at the input, the no load running torque increases 4 times with grease plate and 8 times with grease plate + 10% grease fill for these components.) Through measuring or estimating the starting and running torques internal and external to the drive, the required motor torque was determined.

After calculating the expected torque on the motor shaft as a function of environmental temperature, a thermodynamic model was used to estimate the peak motor rotor temperature during the operating conditions described above. To pass the test, two conditions must be met:

- The motor must not overheat
- The peak armature resistance must be low enough to allow rover system to deliver the current limit for that temperature at the minimum operating voltage (22.5V). Note: As motor's resistance increases, the peak current the system can deliver decreases, for a given voltage.

Given the results of the development testing, the following torque margins were predicted:

**Table 2. Predicted Drive Torque Margins Under Maximum Load at Temperature**

	Temperature		
	-70 C	-60 C	+25 C
Running Torque Margin	1.4	2.0	2.0
Starting Torque Margin	1.5	2.0	2.0

Since a 2.0 torque margin at the minimum protoflight operating temperature (-70°C) could not be predicted, the HGAG drives were all tested and verified at the minimum flight acceptance operating temperature (-60°C).

*Pointing Accuracy Analysis*

The maximum uncertainty in each drive's pointing angle was conservatively estimated by summing the following sources of error at each level of the gear train.

- Detent forcing the motor shaft into the subsequent detent well: 90 deg at motor shaft (or 0.017 deg at the drive's output)
- Backlash in the gearbox: 0.37 deg at gear motor output (or 0.006 deg at the drive's output)
- Backlash in the spur gear stage: 0.14 deg at spur gear output (or 0.003 deg at the drive's output)
- Hysteresis and repeatability error within the harmonic drive: 0.02 deg at the drive's output
- Gear train windup on Mars (Under starting torque condition): 0.07 deg for Azimuth drive and 0.06 deg for Elevation drive
- Expected tolerance stack of housing misalignments (including thermal distortions): 0.186 deg

The total HGAG maximum pointing uncertainty was then found by an RSS combination of each drive's error. The maximum estimated uncertainty in the HGAG's pointing angle was 0.43 deg, which met the 0.5 deg requirement.

*Backdriving Analysis*

When the Rover drives over uneven terrain, the induced g-loading may apply a torque on the azimuth and elevation drives. Since the elevation drive was nearly balanced, the induced loading would have to be very large to cause any concern. The azimuth drive, however, was more susceptible to back driving since its center of mass was offset from its rotation axis by

approximately 150 cm. In order to estimate whether the azimuth drive could withstand the maximum expected 6.6 g loading without back driving, the maximum expected drive train efficiencies were conservatively estimated:

- Harmonic drive back drive torque: 0 Nm
- Harmonic drive starting torque: 0 Nm
- Planetary and spur gear efficiency: 1.0
- Harmonic drive efficiency: 0.85
- Minimum detent holding torque: 2.7 mNm

Using these assumptions, the azimuth drive could only withstand a 2.2 g load before it would start to back drive. Because the drive could not meet the 6.6 g requirement without any movement it was important to understand how much movement would result from the event. A finite element analysis indicated that the 6.6 g loading resembled a 20Hz sine wave that would decay over 1 second. Under this condition, it was estimated that the maximum angular excursion for the drive would be 0.07 deg. This 0.07degree excursion was deemed acceptable by the MER system. In addition, it was determined that the minimum motor detent size required to stop motion would be 1.6 mNm which is well below the minimum detent holding torque of 2.7 mNm for the HGAG motors.

#### *Drive Impact Analysis*

To ensure that the drive would not damage itself when driving into a hard stop, the maximum torque that would develop as the hard stop halted motion was determined. This was found by estimating the total inertia of the moving parts, the maximum angular velocity, the torsional stiffness of the gear train, and the maximum contribution of the detent in adding to the detent torque. Since the reflected inertia of the gear train increases with the square of the gear ratio, the majority of the total inertia was the gear train's early stages. In fact, the inertia of components attached to the motor shaft was 10 times larger than the inertia of the entire mass attached to the drive's output. Fortunately, the harmonic drive's torsional compliance mitigated the peak torque developed and helped to ensure that no damage would occur when the drive impacts the hard stops.

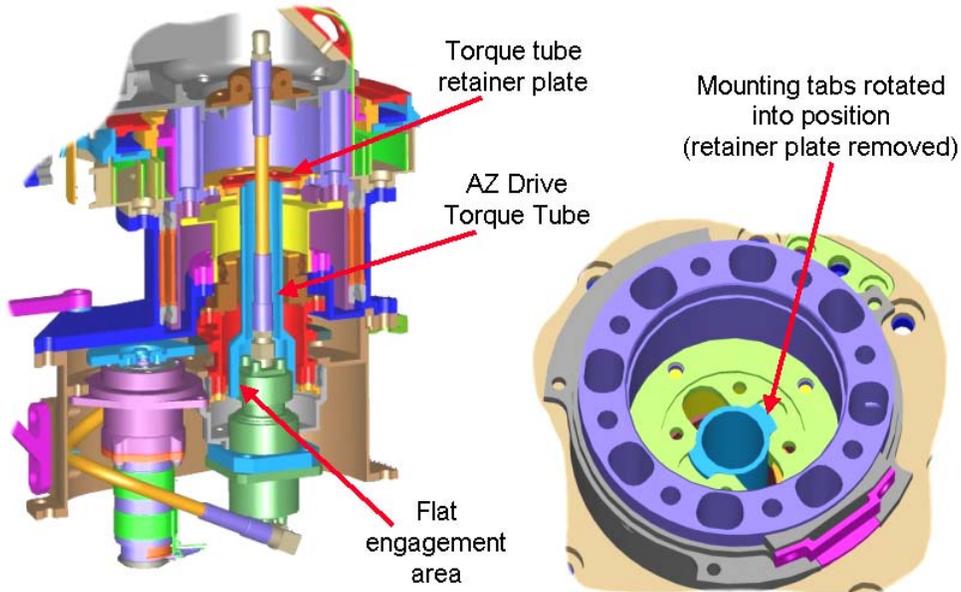
#### RF System

Once the drives have correctly positioned the High Gain Antenna to send and receive communication signals, the HGAG must provide an RF system to transfer that information from the antenna to the Rover electronics. The HGA and coax routing within the gimbal comprise the RF system. The HGA used was almost identical to the HGA used for the Mars Pathfinder Lander, with structural modifications made to accommodate the cantilevered mounting on the HGAG. Given the 0.5 dB maximum loss requirement, it was important to minimize RF cable length and the number of RF fitting interfaces used, in order to limit transmission and insertion losses.

The RF signal must be carried across both the rotating elevation and azimuth drives of the gimbal. It was not desirable to accommodate the large rotation angles required in the drives through bending or flexing of the RF cables. To avoid this, the design employs two RF rotary joints to transmit the signal over the rotating interfaces. The rotary joints are positioned internal to the gimbal and are aligned with the axis of the azimuth and elevation drives. The hollow center design of the drive train allows the RF system to be located right on the center axis of each drive which simplifies the overall RF system. Routing the RF system predominantly internal to the HGAG also helps to protect the cables and rotary joints from damage as well as large temperature gradients. The rotary joints were supplied by Kevlan Corporation under contract from JPL. In order to limit the amount of torque required to rotate the RF joints, small heaters are placed near the bearings in the joints in order to maintain a minimum operating temperature. Between the two rotary joints, the RF signal is carried through semi-rigid coax cables supplied by W.M. Gore under contract from JPL.

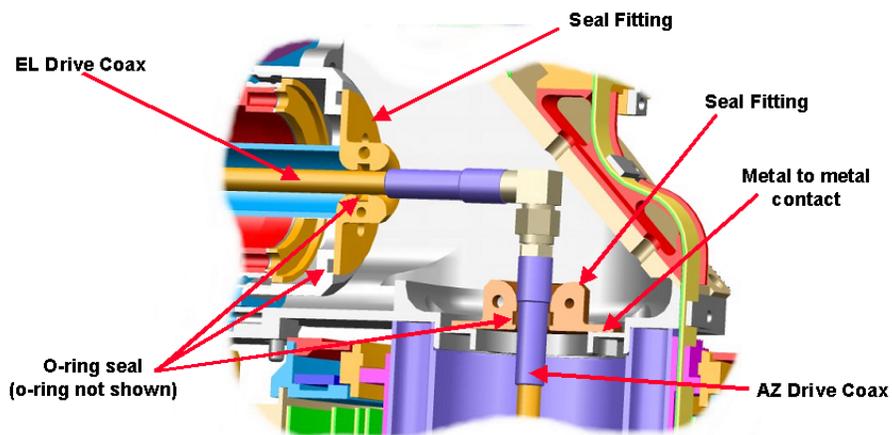
The final RF design areas that needed to be addressed were how to provide the torque required to turn the rotary joints without carrying the torsion load through the semi-rigid RF cables, and how to protect the internal drive components from contamination entering through the RF system. In order to prevent the rotary joint torsion load from being carried by the cables, a "torque tube" is attached to each drive output. The torque tube reaches back down the center hole in each drive and engages two flats on the input to

the rotary joint. As the drive turns, the torque tube provides the force required to turn the rotary joint. Because of the clearance fit required between the torque tube and the rotary joint for assembly reasons, the RF cable is required to accommodate a small amount of rotation prior to the torque tube engaging. However, this small amount of torsion is within the capability of the semi-rigid coax cable. Figure 4 shows the torque tube arrangement.



**Figure 4. RF system torque tube**

A seal system is used to prevent contamination from entering the drive train at the point where the RF system exits the drive. An O-ring is slipped over the RF cable prior to final assembly. During final assembly, the O-ring is located into the groove of a two-piece seal clamp that is mounted to the output of each drive. Figure 5 indicates the seal location and design.

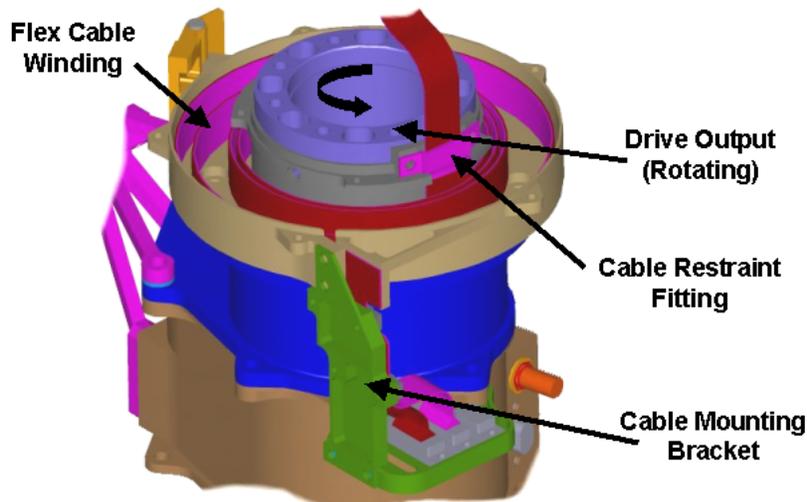


**Figure 5. RF coax contamination seal**

### Flex Cable System

The gimbal design requires that electrical power and signals be passed across both the rotating azimuth and elevation drives. To accomplish this, flex cable twist capsules were used at the output of each drive. The flex cables are wound inside the capsules “clock spring” style, and wind and unwind as the drive rotates. Care was taken to size the flex cable lengths to prevent the system from binding up at either end

of travel as well as allow for shrinkage in the cable lengths due to decreases in temperature. The housing that forms the floor and outside diameter of the twist capsule is also used to clamp the outside race of the main angular contact bearing pair. Once the cables are installed, the radial potentiometer locates on the top of the outside walls of the capsule and forms the lid of the system. The azimuth drive incorporates two flex cables wound as a pair while the elevation drive uses a single flex cable. In order to prevent contamination from entering the system, a potting compound is used to seal the cable exit and entry points at final assembly. Outside of the twist capsules, the flex cables are routed external to the gimbal housings by a system of cable tracks and tie downs. Figure 6 shows the basic installation of the flex cables into the gimbal azimuth drive.



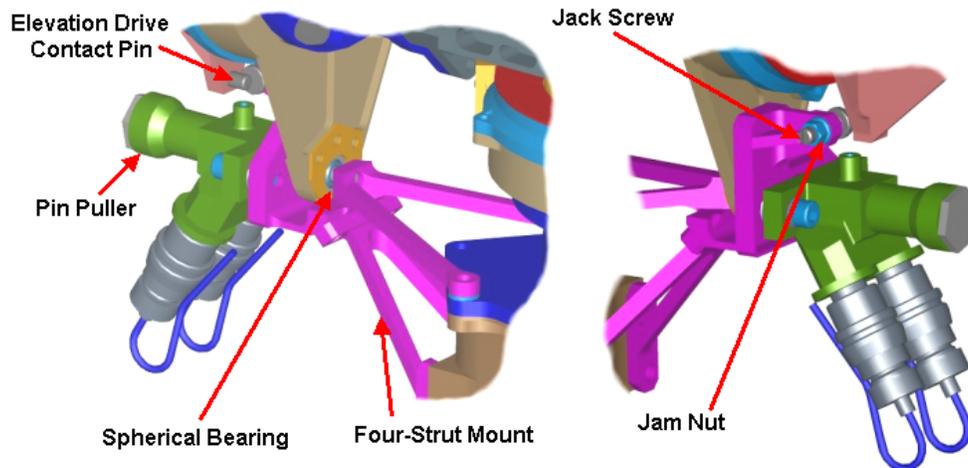
**Figure 6. Flex cable twist capsule installation**

#### Launch Lock System

The requirement for the first mode fundamental frequency of the gimbal during peak environmental loading as well as the need to prevent the drives from back driving during these loads necessitated the use of a locking system. The locking system on the HGAG uses a single pyrotechnic pin puller with redundant NSI charges and an adjustable contact pad to restrain both the azimuth and elevation drives. The pin puller and contact pad are cantilevered off the lower azimuth drive housing using a four-strut mount. The pin in the pyrotechnic device engages an integrally machined flange in the elevation drive twist capsule housing. The interface between the pyrotechnic pin and the housing flange is a spherical bearing that is mounted into the end of the flange. The spherical bearing helps to prevent over constraining the assembly. The bearing also accommodates any angular misalignment that exists between the four-strut mount and the housing flange that could result in increased pin pullout force or binding. Because the housing flange is attached to the static portion of the elevation drive, this system only effectively restrains the azimuth drive from rotating. A second locking feature is required to lock the elevation drive. The elevation drive locking system uses both the elevation drive internal hard stop and an external adjustable contact pad to prevent drive rotation in either direction. The contact pad is threaded into a hole in the same four-strut mount that supports the pyrotechnic pin puller. Once the elevation drive has been positioned for launch, the contact pad is adjusted until it contacts a pin feature on the HGA support arm (located on the rotating output stage of the elevation drive). After it is adjusted, it is locked in place using a pair of locking nuts.

The basic procedure for initially setting up the launch lock system is as follows: The azimuth drive is driven to its launch position using motor encoder feedback. At this point, the azimuth drive is not located against any of its internal hard stops because the pyrotechnic pin will restrain azimuth drive rotation in both directions once it is installed. The elevation drive is also driven to its launch position. For launch and landing, the elevation drive is located against one of its internal hard stops to prevent rotation in one direction. After both drives have been positioned, the four-strut mount and pyrotechnic pin puller assembly are positioned in the vertical plane such that the pin moves freely in and out of the spherical

bearing. The two horizontal mounting pads of the four-strut mount are then shimmed and fastened. The final step is to adjust the elevation drive contact pad until it just touches the feature on the HGA arm and then lock it in place using the two jam nuts. During subsequent re-stowing operations, the four-strut mount is not readjusted. The drives are simply driven back to their launch positions and the pyrotechnic pin puller is reinstalled. This mount provides the system with the additional structural stiffness required to achieve the 50 Hz first mode fundamental frequency requirement during launch and landing. Figure 7 shows the launch locking features on the HGAG.

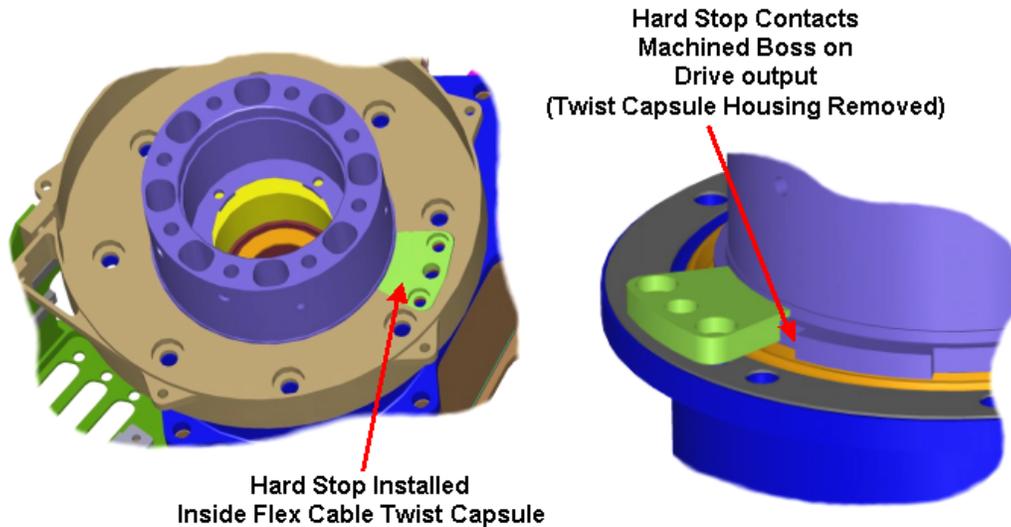


**Figure 7. HGAG launch lock features**

Pyrotechnic restraint devices are used in a number of mechanisms throughout the MER system and underwent a number of development tests throughout the life of the program. One significant design issue that was discovered during this testing is that the shock load induced by the pyrotechnics has the ability to damage the brush DC motors (as well as other sensitive components) that are being used on all the MER mechanisms. Locating the pyrotechnic device a sufficient distance away from any motor, or attempting to try and isolate the pyrotechnic mount from the rest of the system mitigates the risk. On the HGAG, there was concern that the pyrotechnic device was located too close to the azimuth drive motor and that the four-strut mount provided a direct path between the pyro-shock and the motor. Analysis results were inconclusive, so it was decided to verify the design through additional testing. Final design validation was performed on the Engineering Model (EM). The EM was fitted with a redundant pyrotechnic pin puller whose two charges were rated at 120% those of the flight design. Both charges were fired simultaneously and the motor survived the test. Additional pyrotechnic event tests were performed by JPL at the MER system integration level, including tests at the cold operating temperatures. In all cases, no performance effects were seen on the HGAG drive motors.

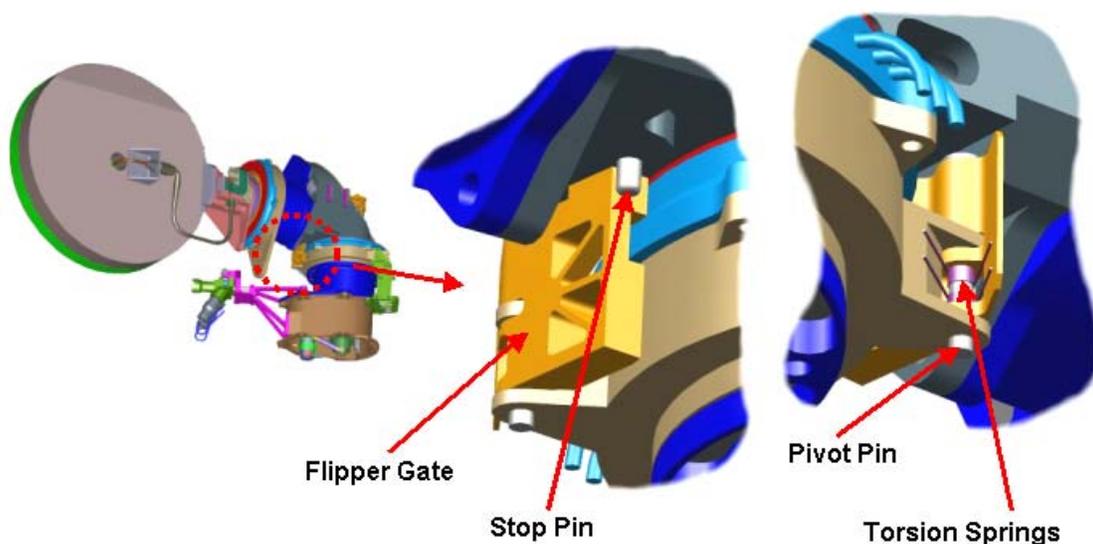
#### Internal Hard Stops and Azimuth Drive “Flipper” Hard Stop

Both the azimuth and elevation drives employ internal hard stops at the end of travel for each drive. These stops provide a consistent mechanical “home” for the drive electronics and prevent the mechanism from exceeding its dynamic envelope and damaging any of the other hardware on the MER. The hard stops consist of an integrally machined titanium boss on the rotating output housing of each drive and a stationary Nitronic 60 hard-stop that is pinned and fastened to the stationary portion of the drive. The Nitronic 60 piece is removable to allow for continuous drive rotation during subassembly testing, but the interface is designed to remain repeatable after consecutive installations. The stop materials were chosen to prevent galling in the system. Figure 8 shows the internal hard-stop features.



**Figure 8. Drive internal hard stop features**

In addition to the internal hard stops, the azimuth drive must also provide a secondary hard stop that is engaged after the first azimuth drive deployment. This secondary stop is necessary because the dynamic sweep envelope of the High Gain Antenna on the elevation drive can violate the envelope of the Low Gain Antenna if the azimuth drive is in its launch locked position. To avoid this, during its first sweep away from the launch position, a pin feature on the azimuth drive passes through a spring-loaded “flipper stop” that closes behind the drive once the pin feature has passed. The new “flipper” hard stop will only allow the azimuth drive to return within 15 degrees of the original launch lock position. At this spot, the elevation drive is free to rotate the HGA through its full dynamic envelope without endangering the Low Gain Antenna. The flipper stop employs two redundant torsion springs that are sized to independently provide enough closing force to keep the flipper secure against the housing during launch and landing. The materials of the pin feature and flipper as well as the shape of the sliding surfaces were chosen to minimize the torsion load required to pass through the spring-loaded gate. Drive level testing was performed to verify the starting / running torque required to pass through the gate as well as to verify the repeatability and strength of the stop under numerous hard stop contacts. Figure 9 shows the secondary azimuth drive “flipper” hard stop.



**Figure 9. Azimuth drive “flipper” hard stop**

Structural Analysis Overview

Two of the significant driving requirements for the HGAG system were the launch locked first fundamental frequency of 50 Hz and the deployed first fundamental frequency of 14 Hz. A detailed finite element model of the HGAG assembly was developed to predict the overall stiffness of the system and assist in finalizing the design. The model was statically and dynamically calibrated to provide accurate mass distribution.

Stiffness predictions for the elevation and azimuth bearing sets were determined using BEAR3D [2], a nonlinear program that allows the analysis of three-dimensional assemblies of linear elastic beams and bearings. The computer program is based on the stiffness method of structural analysis and the bearing technology presented in the New Departure Engineering Handbook of 1946 [3]. The New Departure developments were established for two-dimensional bearing analysis. The techniques were extended to full three-dimensional analysis with five degrees of freedom to represent each bearing. BEAR3D generates a bearing stiffness matrix that is easily incorporated into a MSC.NASTRAN structural system model of the mechanism. In addition to the bearing stiffness predictions, the minimum manufacturer published values were used for the harmonic drive spring rate.

Nonstructural lumped masses include the gear motors, the HGA, the pyrotechnic pin puller, and the potentiometers. All lumped masses were attached to the structure in such a way as to not stiffen, nor strengthen it. The pin puller mount was modeled as four titanium bars of square cross-section. The pin puller was solidly attached to the apex of this four-strut mount. The modal predictions and test results are shown in Table 3. The deployed first mode is largely dependant on the spring rate of the harmonic drive. Because the lowest published value for the spring rate was used in the FEA model, the prediction was lower than the actual test results achieved by the flight hardware.

**Table 3. First mode frequencies of the HGAG with the HGA attached**

	Launch Locked	Deployed
Requirement	50 Hz	14 Hz
Predicted	54 Hz	19.5 Hz
Actual	51 Hz	26 Hz

Analysis was also performed on the structural stresses in the assembly induced by launch, landing, and mobility loads as well as thermal gradients experienced while operating on Mars. For the launch and landing loads, the 45 g quasi-static load was applied to the model in each of the three primary orthogonal axis with the launch lock restraint engaged. For the mobility loads, the expected maximum g load was applied in each of the 3 axis with the launch lock restraint eliminated. In all cases, the structural elements of the gimbal showed acceptable positive margin.

The HGAG is exposed to the environmental temperature extremes during Martian operation. The thermal stress analysis for the structure was done using the same FEA model. Overall system temperature changes (-120°C to +110°C) induce no appreciable stress in the system because all the structural elements are either identical (titanium) or closely matched in CTE (440C steel bearings). However, thermal gradients in the gimbal system can develop from some components seeing direct sunlight while others remain in the shade. It was important to analyze whether or not these gradients could induce enough additional load in the pyrotechnic pin puller system to cause it to bind prior to being fired. The worst-case gradients come from the hot transient case. During this transient case, it was predicted that the assembly could develop a 17.9 MPa peak stress and a 9.8 N side load on the launch lock pin. This result was found to be well within the performance capabilities of the pyrotechnic device.

## HGAG Test Discussion

The HGAG Mechanism test verification plan included individual drive testing and full assembly level testing under all operating conditions. Each individual drive was characterized for performance (including torque speed curves, current limits, pointing accuracy, and stiffness) prior to being integrated together to form a complete HGAG assembly. System level verification tests included structural, RF system loss, pointing accuracy, and dimensional compliance. Every attempt was made to simulate the Martian operating environment for design verification. Thermal vacuum chambers were used to achieve the low operating temperatures and low atmospheric pressures required. Many tests were run with the gimbal mounted on an incline or working against weight and pulley systems to simulate the possible operating orientations and drive loads aboard the rover. After each significant testing milestone, a standardized ambient functional test was performed on the entire system to monitor the health of the mechanisms and ensure that no performance degradation was seen. At the end of its testing protocol, the Engineering Model (EM) underwent a rigorous life test where each drive was cycled under the maximum expected load for the total required number of motor revolutions. In the end, the HGAG units were shown to meet or exceed all design requirements. Figure 10 shows one of the flight HGAA assemblies just prior to shipment to JPL for Rover integration. The thermocouple wire bundles that can be seen coming from different locations on the HGAG were used by JPL during system level testing and were removed or clipped by JPL prior to flight.

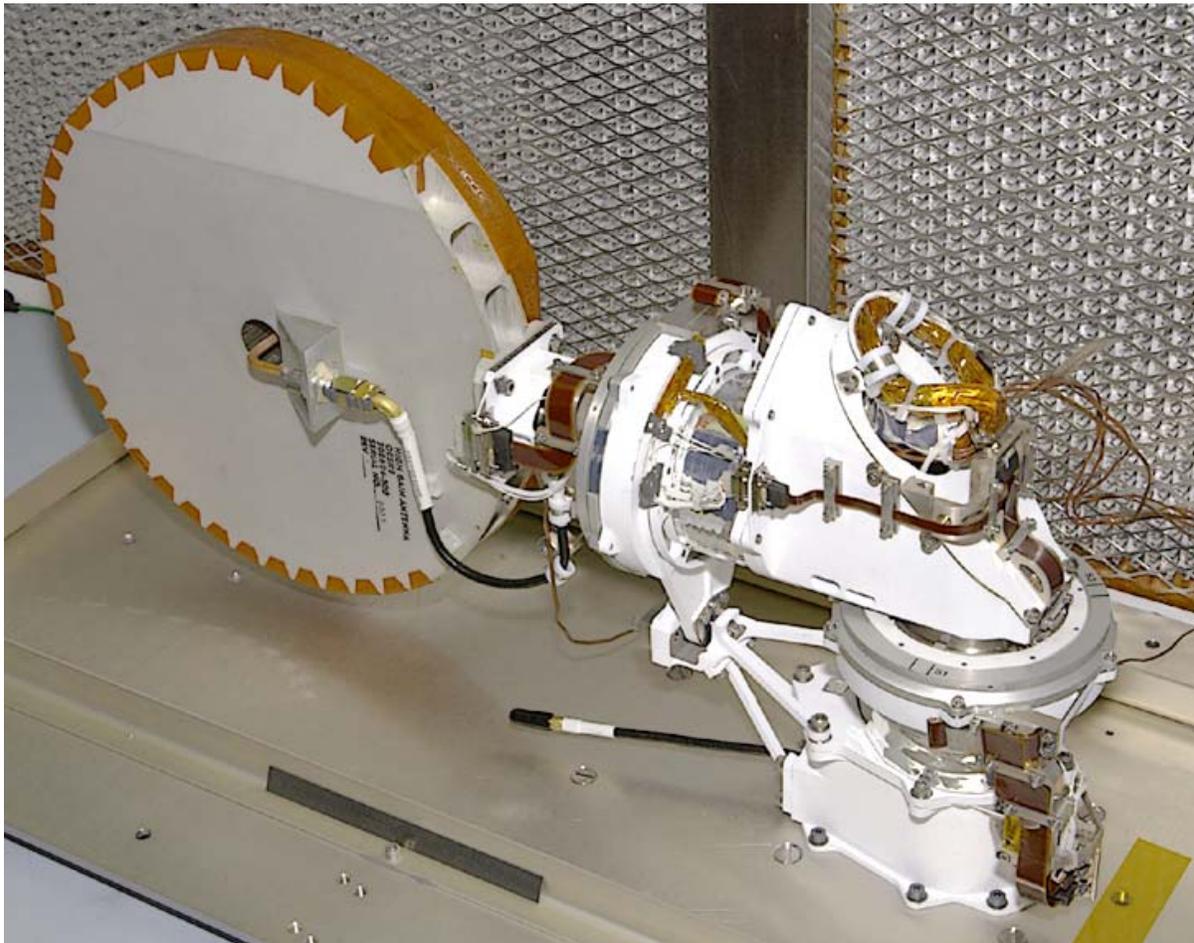


Figure 10. Flight HGAA shown just prior to shipment to JPL

## Conclusion

The design, assembly, test, and delivery of the HGAG mechanisms were a cooperative effort between JPL and BATC. It is difficult to capture all of the lessons learned on a development program such as this, but it is safe to say that all personnel involved with the HGAG program received a valuable education in what it takes to deliver qualified flight hardware for a time sensitive planetary exploration mission. One design lesson that does stick out because of its risk to the HGAG program is the potential damaging effects of the shock load created by pyrotechnic launch lock devices like the pin puller. Care must be taken to properly isolate sensitive components (electronics, motors, etc.) whenever possible. In the case of the HGAG, the problem was discovered late and could not be shown to be acceptable analytically. This required additional verification testing, which in turn introduced additional risk, schedule, and cost late in the program. Fortunately, the design was proven to be robust through testing and any potential redesign was avoided. The HGAG successfully met the design and schedule challenges that it faced, and is on its way to play an important role in the communication system of the MER mission.

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